Is Thick Brane Model Consistent with Recent Observations?

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There exist many observational evidences implying the expansion of our universe is undergoing a late-time acceleration, the mechanism of this acceleration is yet unknown. In the so-called thick brane model this phenomena is attributed to the thickness of the brane along the extra dimension. In this study we mainly rely to the consistency of this model with most recent observational data related to the background evolution. The new Supernova Type Ia (SNIa) Gold sample and Supernova Legacy Survey (SNLS) data, the position of the acoustic peak at the last scattering surface from the Wilkinson Microwave Anisotropy Prob (WMAP) observations and the baryon acoustic oscillation peak found in the Sloan Digital Sky Survey (SDSS) are used to constrain the free parameter of the thick codimension 1 brane model. To infer its consistency with age of our universe, we compare the age of old cosmological objects with what computed using the best fit values for the model parameters. When the universe is matter dominated, $w = 0$, at 68% level of confidence, the combination of Gold sample SNIa, Cosmic Microwave Background (CMB) shift parameter and SDSS databases provides $\Omega_m = 0.31^{+0.02}_{-0.02}$, $\Omega_C = 0.05^{+0.01}_{-0.01}$, $w_r = -1.40^{+0.20}_{-0.20}$, hence a spatially open universe with $\Omega_k = 0.21^{+0.08}_{-0.08}$. The same combination with SNLS supernova observation gives $\Omega_m = 0.28^{+0.03}_{-0.02}$, $\Omega_C = 0.037^{+0.003}_{-0.004}$, $w_r = -2.05^{+0.15}_{-0.15}$ consequently provides a spatially open universe $\Omega_k = 0.11^{+0.10}_{-0.07}$. These results obviously seem to be in contradiction with the most recent WMAP results indicating a flat universe.

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I. INTRODUCTION

Recent observations of type Ia supernovas (SNIa) suggest that the expansion of the universe is accelerating [1–4]. As is well known all usual types of matter with positive pressure generate attractive forces, which decelerate the expansion of the universe. Given this, a dark energy component with negative pressure was suggested to account for the invisible fuel that drives the current acceleration of the universe. There are a huge number of candidates for the dark energy component in the literature (see, e.g., [5–10] for recent reviews), such as a cosmological constant Λ [6,11–13], an evolving scalar field (referred to by some as quintessence: [14–26], the phantom energy, in which the sum of the pressure and energy density is negative [19,27,28], the quintom model [17,29], the holographic dark energy [30], the Chaplygin gas [31,32], and the Cardassion model [29,33,34]. Another approach dealing with this problem is using the modified gravity by changing the Einstein-Hilbert action. Some of models as $1/R$ and logarithmic models provide an acceleration for the universe at the present time [33,35,36].

In addition to the phenomenological modifications of the action, the brane cosmology also implies modification on the dynamics of the universe. Many different Brane models have been presented in the recent years. In one of the best studied models, a codimension 1 thin brane with an infinite extra dimension has been investigated. This brane is embedded in a bulk where its curvature to be negative and its volume is finite [37]. In this sce-

nario, gravitation is localized on a brane reproducing effectively four-dimensional gravity at large distances due to the warp geometry of the spacetime. Usually the brane is modeled as a distributional source in the energy-momentum tensor (EMT) of zero thickness, and in this case the cosmology has been obtained and analyzed in detail [38,39]. Recognizing the difficulty of handling thick walls within relativity, already early authors considered the idealization of a singular hypersurface as a thin wall and tried to formulate its dynamics within general relativity [40]. The new era of intense interests in thin shells and walls began with the development of ideas related to phase transitions in early universe and the formation of topological defects. Again, mainly because of technical difficulties, strings and domain walls were assumed to be infinitesimally thin [41].

Thereafter, interest in thin walls, or hypersurfaces of discontinuity, received an impetus from the cosmology of early universe. The formulation of dynamics of such singular hypersurfaces was summed up in the modern terminology by Israel [42]. Within the Sen-Lanczos-Israel (SLI) formalism, thin shells are regarded as idealized zero thickness objects, with a δ-function singularity in their energy-momentum and Einstein tensors.

In contrast to thin walls, thickness brings in new subtleties, depending on how the thickness is defined and handled. Early attempts to formulate thickness, being mainly motivated by the outcome of the idea of late phase transition in cosmology [43], were concentrated on domain walls. Bonjour et al., studied a thick gravitating domain wall for a general potential [44,45]. Using

general analytical arguments they have shown that all nontrivial solutions fall into two categories: those interpretable as an isolated domain wall with a cosmological event horizon, and those which are pure false vacuum de Sitter solutions. Also they have analyzed the domain wall in the presence of a cosmological constant finding the two kinds of solutions, wall and de Sitter, even in the presence of a negative cosmological constant. Silveria [46] studied the dynamics of a spherical thick domain wall by appropriately defining an average radius for the wall. Widrow [47] used the Einstein-scalar equations for a static thick domain wall with planar symmetry. He then took the zero-thickness limit of his solution and showed that the orthogonal components of the energy-momentum tensor would vanish in that limit. Garfinkle and Gregory [48] presented a modification of the Israel thin shell equations by using an expansion of the coupled Einstein-scalar field equations describing the thick gravitating wall in powers of the thickness of the domain wall around the well-known solution of the hyperbolic tangent kink for a $\lambda\phi^4$ wall and concluded that the effect of thickness at first approximation was effectively to reduce the energy density of the wall compared to the thin case, leading to a faster collapse of a spherical wall in vacuum. Others [49] applied the expansion in the wall action and integrate it out perpendicular to the wall to show that the effective action for a thick domain wall in vacuum apart, from the usual Nambu term, consists of a contribution proportional to the induced Ricci curvature scalar.

Study of thick branes in the string inspired context of cosmology began almost simultaneously with the study of thin branes, using different approaches. Although in brane cosmology the interest is in local behavior of gravity and the brane, most of the authors take a planar brane for granted [50]. However, irrespective of the spacetime dimension and the motivation of having a wall or brane, as far as the geometry of the problem is concerned, most of the papers are based on a regular solution of Einstein equations on a manifold with specified asymptotic behavior representing a localized scalar field [51]. Some authors use a smoothing or smearing mechanism to modify the Randall-Sundrum ansatz [52,53]. Authors in [53] introduce a thickness to the brane by smoothing out the warp factor of a thin brane world to investigate the stability of a thick brane. In another approach to derive generalized Friedmann equations, the four-dimensional effective brane quantities are obtained by integrating the corresponding five-dimensional ones along the extra-dimension over the brane thickness [54]. These cosmological equations describing a brane of finite thickness interpolate between the case of an infinitely thick brane corresponding to the familiar Kaluza-Klein picture and the opposite limit of an infinitely thin brane giving the unconventional Friedmann equation, where the energy density enters quadratically. The latter case is

then made compatible with the conventional cosmology at late times by introducing and fine tuning a negative cosmological constant in the bulk and an intrinsic positive tension in the brane [55]. A completely different approach based on the gluing of a thick wall considered as a regular manifold to two different manifolds on both sides of it was first suggested in [56]. The idea behind this suggestion is to understand the dynamics of a localized matter distribution of any kind confined within two metrically different spacetimes or matter phases. Such a matching of three different manifolds is envisaged to have many diverse applications in astrophysics, early universe, and string cosmology. Authors in [57] studied such a thick brane to obtain the cosmological evolution of the brane. Navarro and Santiago [58] considered a thick codimension 1 brane including a matter pressure component along the extra dimension in the energy-momentum of the brane. By integrating the 5D Einstein equations along the fifth dimension, while neglecting the parallel derivatives of the metric in comparison with the transverse ones, they write the equations relating the values of the first derivatives of the metric at the brane boundary with the integrated components of the brane energy-momentum tensor. These, so called matching conditions are then used to obtain the cosmological evolution of the brane which is of a non-standard type, leading to an accelerating universe for special values of the model parameters. They show that when one drops the infinitesimally thin idealization in the modelling of the brane, gets non-standard cosmology on the brane.

In Section II we make a review over the model first introduced by Navarro and Santiago, the cosmology of a thick codimension 1 brane model, its free parameters and modified Friedman equation which governs the background dynamics of the universe. Then we show how this model can produce an accelerating universe. In Section III we put some constraints on the parameters of model by the background evolution, such as new Gold sample and Legacy Survey of Supernova Type Ia data [3], the combination with the position of the observed acoustic angular scale on CMB and the baryonic oscillation length scale. In Section IV we study the age of universe in the thick brane model, we also compare the age of the universe in this model with the age of old cosmological structures in this section. Section V contains conclusions and discussions of this work.

II. COSMOLOGY ON THE THICK BRANE

In this section we make a brief review over the model first introduced by Navarro and Santiago to study a thick brane. They consider a thick brane in a Randall-Sundrum model with Z_2 symmetry. To get the cosmo-

logical behavior of the Braneworld, the 5D metric is considered to be as follows:

$$ds^2 = n^2(r,t)dt^2 - a^2(r,t)d\mathbf{x}^2 - e^{2\phi(r,t)}dr^2 \qquad (1)$$

where r is the extra dimension and the thick brane exists in $|r| < \epsilon$, so ϵ is somehow the thickness of the brane. By the Z_2 symmetry we know that the core of the brane is placed at $r = 0$. Now we should write down the 5D Einstein equations in the bulk and using the junction conditions derive the induced dynamics on the brane. But first we need to know the energy momentum tensor of the brane and the bulk. We assume that in the bulk ($|r| > \epsilon$) the EMT is just that of a cosmological constant, $T_N^M = \delta_N^M \Lambda$. And for inside the brane, a thick brane means we have let matter goes through the extra dimension. So, matter is distributed within the thickness of the brane and the 5D energy momentum tensor can be written as follows:

$$T_{N(brane)}^M = diag(T_0^0, T_x^x, T_y^y, T_z^z, T_r^r) \qquad (2)$$

where considering the matter on the brane to be a perfect fluid, T_0^0 is the energy density of matter, T_x^x, T_y^y, T_z^z are the pressure of the matter along the normal coordinates and T_r^r is the pressure along the extra dimension.

But, there is a problem to study this thick brane: what is the suitable junction condition? In the thin wall approximation we consider the brane to be a singular hypersurface with δ-function singularity in their energy-momentum and Einstein tensors. From the Sen-Lanczos-Israel (SLI) formalism we know that the difference of the 4D induced metric's derivatives, on both sides of the thin brane is given by the energy momentum tensor of the matter on the singular hypersurface. But in a thick brane model you can not follow the same procedure, as the matter is distributed along the extra dimension. So, what Navarro and Santiago have done is to integrate over Einstein equations in the $|r| < \epsilon$ region to obtain the suitable matching conditions (they have neglected the first derivative of the metric along the parallel brane coordinates):

$$e^{-\phi} \frac{2n'}{n}|_\epsilon = \frac{1}{M_*^3} \left[\frac{2}{3}\rho + p + \frac{1}{3}p_r \right] \qquad (3)$$

$$e^{-\phi} \frac{2a'}{a}|_\epsilon = \frac{1}{M_*^3} \left[\frac{1}{3}(p_r - \rho) \right] \qquad (4)$$

where prime denotes differentiation with respect to r, M_*^3 is the 5D fundamental mass and ρ, p and p_r respectively are the 4D energy density, longitudinal (along the normal coordinates) and transverse 4D pressure (along the extra dimension), derived by integrating over the EMT along the thickness of the brane:

$$\rho \equiv \frac{1}{na^3|_\epsilon} \int_{-\epsilon}^{\epsilon} T_0^0 na^3 e^\phi dr \qquad (5)$$

$$p \equiv -\frac{1}{na^3|_\epsilon} \int_{-\epsilon}^{\epsilon} T_x^x na^3 e^\phi dr \qquad (6)$$

$$p_r \equiv -\frac{1}{na^3|_\epsilon} \int_{-\epsilon}^{\epsilon} T_r^r na^3 e^\phi dr \qquad (7)$$

Splitting the brane EMT to the constant (λ) and a time dependant part (with an arbitrary but assumed constant equation of motion), we have:

$$\rho = \lambda + \rho_m \quad p = -\lambda + w\rho_m \quad p_r = -\lambda_r + w_r\rho_m \quad (8)$$

Now having the integrated EMT and the junction conditions we can solve the 5D Einstein equations to obtain the cosmological dynamics of the thick braneworld. Evaluating the rr and tr components of the 5D Einstein equations and keeping the terms up to the first order of ρ_m we get:

$$3\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} \right) =$$
$$\frac{1}{12M_*^6} \left[2(\lambda + \lambda_r)^2 + (\lambda + \lambda_r)(1 - 3w - 4w_r)\rho_m \right] + \frac{\Lambda}{M_*^3} \qquad (9)$$

$$\dot{\rho}_m + 3\frac{\dot{a}}{a}(1 + w)\rho_m - w_r\dot{\rho}_m = 0 \qquad (10)$$

where k denotes the curvature and can be $k = (0, 1, -1)$ which respectively gives the spatially flat, closed and open universes, w and w_r are the state parameters related to the longitudinal and the transverse pressures. It can be easily checked that if $w_r = 0$ we obtain the standard cosmology with a cosmological constant given by: $\Lambda_{eff} = \frac{1}{6M_*^6}(\lambda + \lambda_r)^2 + \frac{\Lambda}{M^3})$ up to $\mathcal{O}(\rho_m^2)$. But for a nonzero value of w_r the cosmological evolution on the 4D brane will be completely different. As it can be seen in the equation (10), existing a non zero pressure along the extra dimension violates the EMT conservation in the 4 dimensions:

$$\dot{\rho}_m + 3\frac{\dot{a}}{a}(1 + w)\rho_m = w_r\dot{\rho}_m \neq 0 \qquad (11)$$

One can easily integrate equation (11) to get:

$$\rho_m = \rho_{m0}a^{-3\frac{1+w}{1-w_r}} \qquad (12)$$

where ρ_{m0} is the present matter density. Inserting this result in equation (9) and integrating the equation, assuming $\Lambda_{eff} = 0$, they obtain their generalized Friedman equation as follows:

$$H^2 = \mathcal{C}a^{-4} + \frac{\lambda + \lambda_r}{18M_*^6}(1 - w_r)\rho_{m0}a^{-3\frac{1+w}{1-w_r}} - \frac{k}{a^2} \qquad (13)$$

where $H \equiv \frac{\dot{a}}{a}$ and $\mathcal{C}$ is an integration constant coming from the extra dimension assumption. This equation

shows that having a pressure component of EMT along the extra dimension is similar to having a matter with an effective parameter of state defined as follows:

$$w_{eff} = \frac{w + w_r}{1 - w_r}$$

Also it can be checked from equation (9) that even when $\Lambda_{eff} = 0$ we can have an accelerating universe ($w_{eff} < -1/3$), which means that in the case of having matter as the only source of the Einstein equations ($w = 0$), the evolution of the universe is an accelerating one. So the only required condition is $w_r < -1/2$. Navarro and Santiago discuss that a KK mechanism can produces such a negative pressure by the KK modes. So to have an accelerating universe we require the matter to be confined in the thickness of the brane which causes a negative w_r. They have not studied the dynamics of the universe at early times, whether it is comparable with standard model of cosmology or not. As it can be checked easily, having $w_r < -1/2$, all the time during the evolution of the universe, in the radiation dominated era ($w = 1/3$), equation (13) shows that the second term in the right hand side behaves as a^b where $b > -8/3$, so in the early universe where a is very small, the first term is the dominated term, which corresponds to the radiation dominated ear a^{-4}. So this model is compatible with the standard model of cosmology at the early universe. But the main difference is at the late time, where the second term in the equation (13) is big enough and the effects of the brane thickness becomes important.

In order to compare the predictions of this model with the observational tests, we rewrite equation (13) as a function of dimensionless parameters:

$$H^2(z; \Omega_m, \Omega_{\mathcal{C}}, w, w_r) = H_0^2 [\Omega_{\mathcal{C}}(1 + z)^4$$
$$+ \Omega_m (1 - w_r)(1 + z)^{3\frac{1+w}{1-w_r}} - (\Omega_{tot} - 1)(1 + z)^2] \quad (14)$$

where $M_p^2 = 6\frac{M_*^6}{\lambda + \lambda_r}$, $\Omega_{\mathcal{C}} \equiv \frac{\mathcal{C}}{H_0^2}$, z is the redshift, Ω_m is the present matter density (for simplicity we discard its zero indice) and $\Omega_{tot} = \Omega_m(1 - w_r) + \Omega_{\mathcal{C}} = 1 + \Omega_k$.

In the case of having just energy density of matter as the only source of the background dynamics of the universe, we have $w = 0$. For an object with the redshift of z, using the null geodesics in the FRW metric induced on the brane, comoving distance is obtained as:

$$r(z; \Omega_m, \Omega_{\mathcal{C}}, w_r, w) = \frac{1}{H_0 \sqrt{|\Omega_k|}}$$
$$\mathcal{F}\left(\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')/H_0}\right)$$
$$(15)$$

where

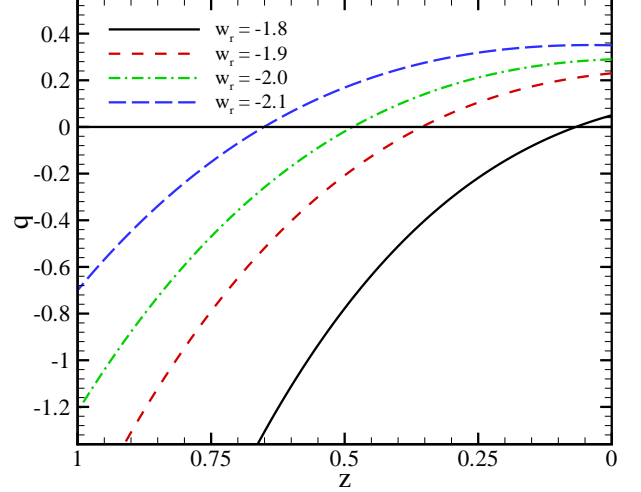$$\mathcal{F}(x) \equiv (x, \sin x, \sinh x) \text{ for } k = (0, 1, -1) \quad (16)$$

FIG. 1. Acceleration parameter ($q = \ddot{a}/aH_0^2$) in the thick brane model as function of redshift for various values of w_r. Here $\Omega_k = 0.0$, $w = 0.0$ and $\Omega_m = 0.33$

and $H(z; \Omega_m, \Omega_{\mathcal{C}}, w_r, w)$ is given by equation (14). To see how this models gives an accelerating model we study the behavior of the acceleration parameter ($q = \ddot{a}/H_0^2 a$). According to the equations (9) and (13) in this model accelerating parameter is derived as follows:

$$q = -\Omega_{\mathcal{C}} a^{-4} - \frac{1}{2}(1 + 2w_r + 3w)\Omega_m a^{-3(1+w_{eff})} \quad (17)$$

As it can be seen in figure (1), increasing w_r causes the universe to accelerate earlier.

Now an interesting question that arises is: "can this model predict dynamics of universe?" or in another word, "what values of the model parameter to be consistent with observational tests?"

In the forthcoming sections we will see what constraints to the model described above are set by recent observations.

III. OBSERVATIONAL CONSTRAINTS ON THE MODEL USING BACKGROUND EVOLUTION OF THE UNIVERSE

In this section, at first we examine thick codimension 1 brane model by SNIa Gold sample and supernova Legacy Survey data. Then to make the model parameter intervals more confined, we will combine observational results of SNIa distance modules with power spectrum of cosmic microwave background radiation and baryon acoustic oscillation measured by Sloan Digital Sky survey. Table I shows different priors on the model parameters used in the likelihood analysis.
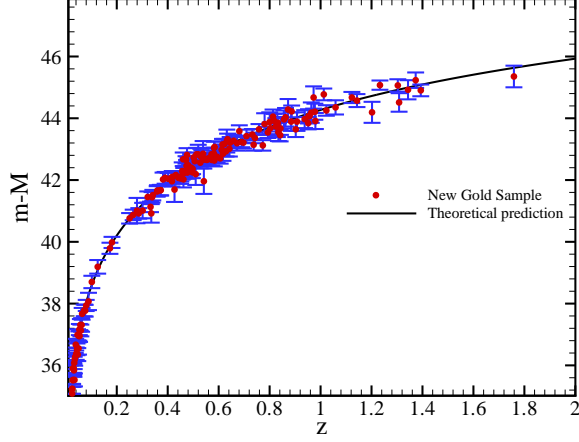
FIG. 2. Distance modulus of the SNIa new Gold sample in terms of redshift. Solid line shows the best fit values with the corresponding parameters of $h = 0.63$, $\Omega_m = 0.16^{+0.84}_{-0.03}$, $\Omega_\mathcal{C} = 0.20^{+0.04}_{-0.19}$ and $w_r = -5.80^{+4.80}$ in 1σ level of confidence with $\chi^2_{min}/N_{d.o.f} = 0.92$ for thick brane model.
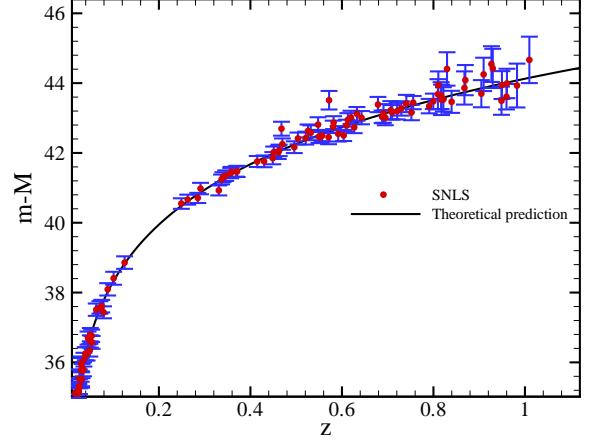

FIG. 3. Distance modulus of the SNLS supernova data in terms of redshift. Solid line shows the best fit values with the corresponding parameters of $h = 0.70$, $\Omega_m = 0.39^{+0.47}_{-0.26}$, $\Omega_\mathcal{C} = 0.054^{+0.056}_{-0.053}$ and $w_r = -1.80^{+0.70}$ in 1σ level of confidence with $\chi^2_{min}/N_{d.o.f} = 0.86$ for thick brane model.

TABLE I. Priors on the parameter space, used in the likelihood analysis.

Parameter	Prior	
$\Omega_{tot} = (1 - w_r)\Omega_m + \Omega_\mathcal{C}$	1.00	Fixed
$\Omega_{tot} = (1 - w_r)\Omega_m + \Omega_\mathcal{C}$	-	Free
Ω_m	$0.00 - 1.00$	Top hat
$\Omega_b h^2$	0.020 ± 0.005	Top hat (BBN) [59]
h	$-$	Free [60,61]
w_r	$-100.00 - 0.00$	Top hat
w	0	Fixed

A. Supernova Type Ia: Gold and SNLS Samples

The Supernova Type Ia experiments provided the main evidence of the existence of dark energy. Since 1995 two teams of the *High-Z Supernova Search* and the *Supernova Cosmology Project* have discovered several type Ia supernovas at the high redshifts [22,62]. Recently Riess et al.(2004) announced the discovery of 16 type Ia supernova with the Hubble Space Telescope. They determined the luminosity distance of these supernovas and with the previously reported algorithms, obtained a uniform 157 Gold sample of type Ia supernovas [3,4,63]. Recently a new data set of Gold sample with smaller systematic error containing 156 Supernova Ia has been released [64]. In this work we use this data set as new Gold sample SNIa.

More recently, the SNLS collaboration released the first year data of its planned five-year Supernova Legacy

Survey [65]. An important aspect to be emphasized on the SNLS data is that they seem to be in a better agreement with WMAP results than the Gold sample [66].

We compare the predictions of the thick brane model for apparent magnitude with new SNIa Gold sample and SNLS data set. The observations of supernova measure essentially the apparent magnitude m including reddening, K correction, etc, which are related to the (dimensionless) luminosity distance, D_L, of an object at redshift z through:

$$m = \mathcal{M} + 5 \log D_L(z; \Omega_m, \Omega_\mathcal{C}, w_r, w) \qquad (18)$$

where

$$D_L(z; \Omega_m, \Omega_\mathcal{C}, w_r, w) = \frac{(1+z)}{\sqrt{|\Omega_k|}} \mathcal{F}\left(\sqrt{|\Omega_k|} \int_0^z \frac{dz' H_0}{H(z')}\right) \qquad (19)$$

Also

$$\mathcal{M} = M + 5 \log\left(\frac{c/H_0}{1 \quad Mpc}\right) + 25 \qquad (20)$$

where M is the absolute magnitude. The distance modulus, μ, is defined as:

$$\mu \equiv m - M = 5 \log D_L(z; \Omega_m, \Omega_\mathcal{C}, w_r, w)$$
$$+ 5 \log\left(\frac{c/H_0}{1 \quad Mpc}\right) + 25 \qquad (21)$$

or

$$\mu = 5 \log D_L(z; \Omega_m, \Omega_\mathcal{C}, w_r, w) + \bar{M} \qquad (22)$$

In order to compare the theoretical results with the observational data, we must compute the distance modulus, as given by equation (21). For this purpose, the first step is to compute the quality of the fitting through the least squared fitting quantity χ^2 defined by:

$$\chi^2(\bar{M}, \Omega_m, \Omega_\mathcal{C}, w_r, w) =$$
$$\sum_i \frac{[\mu_{obs}(z_i) - \mu_{th}(z_i; \Omega_m, \Omega_\mathcal{C}, w_r, w, \bar{M})]^2}{\sigma_i^2} \quad (23)$$

where σ_i is the observational uncertainty in the distance modulus. To constrain the parameters of model, we use the Likelihood statistical analysis:

$$\mathcal{L}(\bar{M}, \Omega_m, \Omega_\mathcal{C}, w_r, w) = \mathcal{N} e^{-\chi^2(\bar{M}, \Omega_m, \Omega_\mathcal{C}, w_r, w)/2} \quad (24)$$

where $\mathcal{N}$ is a normalization factor. The parameter $\bar{M}$ is a nuisance parameter and should be marginalized (integrated out) leading to a new $\bar{\chi}^2$ defined as:

$$\bar{\chi}^2 = -2 \ln \int_{-\infty}^{+\infty} \mathcal{L}(\bar{M}, \Omega_m, \Omega_\mathcal{C}, w_r, w) d\bar{M} \quad (25)$$

Using equations (23) and (25), we find:

$$\bar{\chi}^2(\Omega_m, \Omega_\mathcal{C}, w_r, w) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\mathcal{C}, w_r, w)$$
$$- \frac{B(\Omega_m, \Omega_\mathcal{C}, w_r, w)^2}{C} + \ln(C/2\pi) \quad (26)$$

where

$$B(\Omega_m, \Omega_\mathcal{C}, w_r, w) =$$
$$\sum_i \frac{[\mu_{obs}(z_i) - \mu_{th}(z_i; \Omega_m, \Omega_\mathcal{C}, w_r, w, \bar{M} = 0)]}{\sigma_i^2} \quad (27)$$

and

$$C = \sum_i \frac{1}{\sigma_i^2} \quad (28)$$

Equivalent to marginalization is the minimization with respect to $\bar{M}$. One can show that χ^2 can be expanded in $\bar{M}$ as [67]:

$$\chi^2_{\mathrm{SNIa}}(\Omega_m, \Omega_\mathcal{C}, w_r, w) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\mathcal{C}, w_r, w)$$
$$- 2\bar{M}B + \bar{M}^2 C \quad (29)$$

which has a minimum for $\bar{M} = B/C$:

$$\chi^2_{\mathrm{SNIa}}(\Omega_m, \Omega_\mathcal{C}, w_r, w) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\mathcal{C}, w_r, w)$$
$$- \frac{B(\Omega_m, \Omega_\mathcal{C}, w_r, w)^2}{C} \quad (30)$$

Using equation (30) we can find the best fit values of model parameters as the values that minimize $\chi^2_{\mathrm{SNIa}}(\Omega_m, \Omega_\mathcal{C}, w_r, w)$. In the following analysis we suppose matter domination era, $w = 0$ unless stated otherwise. As a simplest case we suppose a flat universe,

$\Omega_k = 0.0$. In this situation, the best fit values for the parameters of the model are $\Omega_m = 0.01^{+0.12}_{-0.01}$ and $w_r = -10.00^{+4.69}$ with $\chi^2_{min}/N_{d.o.f} = 0.91$ at 1σ level of confidence. The corresponding value for the Hubble parameter at the minimized χ^2 is $h = 0.63$ and since we have already marginalized over this parameter we do not assign an error bar for it. The best fit values for the parameters of model by using SNLS supernova data are $\Omega_m = 0.16^{+0.28}_{-0.16}$, and $w_r = -4.70^{+3.43}$ with $\chi^2_{min}/N_{d.o.f} = 0.86$ at 1σ level of confidence. The corresponding Hubble parameter is $h = 0.70$.

If we take account Ω_k as another free parameter, we would have got $\Omega_\mathcal{C}$ as free parameter. The best fit values for the parameters of model by using supernova data are $\Omega_m = 0.16^{+0.84}_{-0.19}$, $\Omega_\mathcal{C} = 0.20^{+0.04}_{-0.19}$ and $w_r = -5.80^{+4.80}$ with $\chi^2_{min}/N_{d.o.f} = 0.92$ at 1σ level of confidence. These values imply that $\Omega_k = -0.28^{+5.76}_{-1.62}$. The best fit values for the parameters of model by using SNLS supernova data are $\Omega_m = 0.39^{+0.47}_{-0.26}$, $\Omega_\mathcal{C} = 0.054^{+0.056}_{-0.053}$ and $w_r = -1.80^{+0.70}$ with $\chi^2_{min}/N_{d.o.f} = 0.87$ at 1σ level of confidence. These values imply that $\Omega_k = -0.14^{+1.34}$.

Figures (2) and (3) show the comparison of the theoretical prediction of distance modulus by using the best fit values of model parameters and observational values from new Gold sample and SNLS supernova, respectively. Figures (4), (5), (6) and (7) show relative likelihood for free parameters of thick brane model.

B. Combined analysis: SNIa+CMB+SDSS

Before last scattering, the photons and baryons are tightly coupled by Compton scattering and behave as a fluid. The oscillations of this fluid, occurring as a result of the balance between the gravitational interactions and the photon pressure, lead to the familiar spectrum of peaks and troughs in the averaged temperature anisotropy spectrum which we measure today. The odd peaks correspond to maximum compression of the fluid, the even ones to rarefaction [68]. In an idealized model of the fluid, there is an analytic relation for the location of the m-th peak: $l_m \approx m l_A$ [69,70] where l_A is the acoustic scale which may be calculated analytically and depends on both pre- and post-recombination physics as well as the geometry of the universe. The acoustic scale corresponds to the Jeans length of photon-baryon structures at the last scattering surface some ~ 379 Kyr after the Big Bang [13]. The apparent angular size of acoustic peak can be obtained by dividing the comoving size of sound horizon at the decoupling epoch $r_s(z_{dec})$ by the comoving distance of observer to the last scattering surface $r(z_{dec})$:

$$\theta_A = \frac{\pi}{l_A} \equiv \frac{r_s(z_{dec})}{r(z_{dec})} \quad (31)$$

The size of sound horizon at the numerator of equation (31) corresponds to the distance that a perturbation of

pressure can travel from the beginning of universe up to the last scattering surface and is given by:

$$r_s(z_{dec}; \Omega_m, \Omega_{\mathcal{C}}, w_r, w)$$
$$= \frac{1}{H_0\sqrt{|\Omega_k|}} \times \mathcal{F}\left(\sqrt{|\Omega_k|}\int_{z_{dec}}^{\infty} \frac{v_s(z')dz'}{H(z')/H_0}\right) \quad (32)$$

where $v_s(z)^{-2} = 3 + 9/4 \times \rho_b(z)/\rho_{rad}(z)$ is the sound velocity in the unit of speed of light from the big bang up to the last scattering surface [24,69] and the redshift of the last scattering surface, z_{dec}, is given by [69]:

$$z_{dec} = 1048\left[1 + 0.00124(\omega_b)^{-0.738}\right]\left[1 + g_1(\omega_m)^{g_2}\right]$$
$$g_1 = 0.0783(\omega_b)^{-0.238}\left[1 + 39.5(\omega_b)^{0.763}\right]^{-1}$$
$$g_2 = 0.560\left[1 + 21.1(\omega_b)^{1.81}\right]^{-1} \quad (33)$$

where $\omega_m \equiv \Omega_m h^2$, ρ_{rad} is the radiation density and $\omega_b \equiv \Omega_b h^2$ (Ω_b is the present baryonic density). Changing the parameters of the model can change the size of apparent acoustic peak and subsequently the position of $l_A \equiv \pi/\theta_A$ in the power spectrum of temperature fluctuations on CMB. The simple relation $l_m \approx ml_A$ however does not hold very well for the first peak although it is better for higher peaks. Driving effects from the decay of the gravitational potential as well as contributions from the Doppler shift of the oscillating fluid introduce a shift in the spectrum. A good parameterizations for the location of the peaks and troughs is given by [25,70]

$$l_m = l_A(m - \phi_m) \quad (34)$$

where ϕ_m is phase shift determined predominantly by pre-recombination physics, and are independent of the geometry of the Universe. The location of first acoustic peak can be determined in model by equation (34) with $\phi_1(\omega_m, \omega_b) \simeq 0.27$ [25,70]. Instead of the peak locations of power spectrum of CMB, one can use another model independent parameter which is so-called shift parameter $\mathcal{R}$ as:

$$\mathcal{R} \propto \frac{l_1^{flat}}{l_1} \quad (35)$$

where l_1^{flat} corresponds to flat pure-CDM model with $\Omega_m = 1.0$ and the same ω_m and ω_b as the original model. It is easily shown that shift parameter is as follows [71]:

$$\mathcal{R} = \sqrt{\Omega_m}\frac{D_L(z_{dec}; \Omega_m, \Omega_{\mathcal{C}}, w_r, w)}{(1 + z_{dec})} \quad (36)$$

The observational results of CMB experiments correspond to a shift parameter of $\mathcal{R} = 1.716 \pm 0.062$ (given by WMAP, CBI, ACBAR) [13,72]. One of the advantages of using the parameter $\mathcal{R}$ is that it is independent of Hubble constant. In order to put constraint on the model from CMB, we compare the observed shift parameter with that of model using likelihood statistic as [71]:

$$\mathcal{L} \sim e^{-\chi^2_{\mathrm{CMB}}/2} \quad (37)$$

where

$$\chi^2_{\mathrm{CMB}} = \frac{[\mathcal{R}_{\mathrm{obs}} - \mathcal{R}_{\mathrm{th}}]^2}{\sigma^2_{\mathrm{CMB}}} \quad (38)$$

where $\mathcal{R}_{\mathrm{th}}$ and $\mathcal{R}_{\mathrm{obs}}$ are the theoretical shift parameter, determined using equation (36), and the observed one, respectively.

The large scale correlation function measured from $46,748$ *Luminous Red Galaxies* (LRG) spectroscopic sample of the SDSS (Sloan Digital Sky Survey) includes a clear peak at about 100 Mpc h^{-1} [73]. This peak was identified with the expanding spherical wave of baryonic perturbations originating from acoustic oscillations at recombination. The comoving scale of this shell at recombination is about 150Mpc in radius. In other words this peak has an excellent match to the predicted shape and the location of the imprint of the recombination-epoch acoustic oscillation on the low-redshift clustering matter [73]. A dimensionless and independent of H_0 version of SDSS observational parameter is:

$$\mathcal{A} = D_V(z_{\mathrm{sdss}})\frac{\sqrt{\Omega_m H_0^2}}{z_{\mathrm{sdss}}}$$
$$= \sqrt{\Omega_m}\left[\frac{H_0 D_L^2(z_{\mathrm{sdss}}; \Omega_m, \Omega_{\mathcal{C}}, w_r, w)}{H(z_{\mathrm{sdss}}; \Omega_m, \Omega_{\mathcal{C}}, w_r, w)z_{\mathrm{sdss}}^2(1 + z_{\mathrm{sdss}})^2}\right]^{1/3} \quad (39)$$

where $D_V(z_{\mathrm{sdss}})$ is characteristic distance scale of the survey with mean redshift z_{sdss} [73–75]. We use the robust constraint on the thick brane model using the value of $\mathcal{A} = 0.469 \pm 0.017$ from the LRG observation at $z_{\mathrm{sdss}} = 0.35$ [73]. This observation permits the addition of one more term in the χ^2 of equations (30) and (38) to be minimized with respect to $H(z)$ model parameters. This term is:

$$\chi^2_{\mathrm{SDSS}} = \frac{[\mathcal{A}_{\mathrm{obs}} - \mathcal{A}_{\mathrm{th}}]^2}{\sigma^2_{\mathrm{SDSS}}} \quad (40)$$

This is the third observational constraint for our analysis.

In what follows we perform a combined analysis of SNIa, CMB and SDSS to constrain the parameters of the thick brane model by minimizing the combined $\chi^2 = \chi^2_{\mathrm{SNIa}} + \chi^2_{\mathrm{CMB}} + \chi^2_{\mathrm{SDSS}}$. The best values of the model parameters from the fitting with the corresponding error bars from the likelihood function marginalizing over the Hubble parameter in the multidimensional parameter space in flat universe and domination matter epoch are: $\Omega_m = 0.33^{+0.02}_{-0.03}$ and $w_r = -1.92^{+0.18}_{-0.25}$ at 1σ confidence level with $\chi^2_{min}/N_{d.o.f} = 1.02$. The Hubble parameter corresponding to the minimum value of χ^2 is $h = 0.64$. Here we obtain an age of $15.62^{+3.14}_{-3.91}$ Gyr for the universe (see section IV for more details). Using the SNLS data, the best fit values of model parameters are: $\Omega_m = $

TABLE II. The best values for the parameters of a thick brane model with the corresponding age for the universe from fitting with SNIa from new Gold sample and SNLS data, SNIa+CMB and SNIa+CMB+SDSS experiments at one and two σ confidence level. Here we suppose $\Omega_k = 0.0$ and $w = 0.0$.

Observation	Ω_m	w_r	Age (Gyr)
SNIa(new Gold)	$0.01^{+0.12}_{-0.01}$ $0.01^{+0.33}_{-0.01}$	$-10.00^{+4.69}$ $-10.00^{+98.31}$	$8.06^{+3.14}$
SNIa(new Gold)+CMB	$0.43^{+0.04}_{-0.04}$ $0.43^{+0.09}_{-0.08}$	$-1.24^{+0.22}_{-0.20}$ $-1.24^{+0.39}_{-0.47}$	$15.21^{+3.66}_{-3.57}$
SNIa(new Gold)+ CMB+SDSS	$0.33^{+0.02}_{-0.03}$ $0.33^{+0.05}_{-0.05}$	$-1.92^{+0.18}_{-0.25}$ $-1.92^{+0.37}_{-0.49}$	$15.62^{+3.14}_{-3.91}$
SNIa (SNLS)	$0.16^{+0.28}_{-0.16}$ $0.16^{+0.35}_{-0.16}$	$-4.70^{+3.43}$ $-4.70^{+3.73}$	$12.64^{+8.74}$
SNIa(SNLS)+CMB	$0.33^{+0.05}_{-0.05}$ $0.33^{+0.10}_{-0.09}$	$-1.91^{+0.38}_{-0.53}$ $-1.91^{+0.69}_{-1.23}$	$14.30^{+4.49}_{-4.86}$
SNIa(SNLS)+ CMB+SDSS	$0.28^{+0.02}_{-0.02}$ $0.28^{+0.05}_{-0.04}$	$-2.47^{+0.27}_{-0.30}$ $-2.47^{+0.52}_{-0.64}$	$15.23^{+4.04}_{-4.07}$

TABLE III. The best fit values for the parameters of the model using SNIa from new Gold sample and SNLS data, SNIa+CMB and SNIa+CMB+SDSS experiments at one and two σ confidence level. Here we suppose $w = 0.0$.

Observation	Ω_m	$\Omega_{\mathcal{C}}$	w_r
SNIa(new Gold)	$0.16^{+0.84}_{-0.03}$ $0.16^{+0.84}_{-0.08}$	$0.20^{+0.04}_{-0.19}$ $0.20^{+0.08}_{-0.19}$	$-5.80^{+4.80}$ $-5.80^{+4.90}$
SNIa(new Gold)+CMB	$0.53^{+0.10}_{-0.09}$ $0.53^{+0.16}_{-0.19}$	$0.03^{+0.02}_{-0.02}$ $0.03^{+0.03}_{-0.03}$	$-1.10^{+0.20}_{-0.20}$ $-1.10^{+0.40}_{-0.70}$
SNIa(new Gold)+ CMB+SDSS	$0.31^{+0.02}_{-0.02}$ $0.31^{+0.02}_{-0.02}$	$0.05^{+0.01}_{-0.01}$ $0.05^{+0.01}_{-0.01}$	$-1.40^{+0.20}_{-0.20}$ $-1.40^{+0.20}_{-0.20}$
SNIa (SNLS)	$0.39^{+0.47}_{-0.26}$ $0.39^{+0.61}_{-0.30}$	$0.054^{+0.056}_{-0.053}$ $0.054^{+0.086}_{-0.053}$	$-1.80^{+0.70}$ $-1.80^{+0.80}$
SNIa(SNLS)+CMB	$0.42^{+0.09}_{-0.23}$ $0.42^{+0.12}_{-0.33}$	$0.027^{+0.013}_{-0.023}$ $0.027^{+0.018}_{-0.026}$	$-1.60^{+0.30}_{-1.05}$ $-1.60^{+0.45}_{-5.00}$
SNIa(SNLS)+ CMB+SDSS	$0.28^{+0.03}_{-0.02}$ $0.28^{+0.05}_{-0.04}$	$0.037^{+0.003}_{-0.004}$ $0.037^{+0.008}_{-0.008}$	$-2.05^{+0.15}_{-0.15}$ $-2.05^{+0.35}_{-0.35}$

$0.28^{+0.02}_{-0.02}$ and $w_r = -2.47^{+0.27}_{-0.30}$ at 1σ confidence level with $\chi^2_{min}/N_{d.o.f} = 0.86$. Age of universe calculating with the best fit parameters is $15.23^{+4.04}_{-4.07}$ (see next section). Table II indicates the best fit values for the cosmological parameters with one and two σ level of confidence. In general case, the following values for the free parameters maximize likelihood probability: $\Omega_m = 0.31^{+0.02}_{-0.02}$, $\Omega_{\mathcal{C}} = 0.05^{+0.01}_{-0.01}$ and $w_r = -1.40^{+0.20}_{-0.20}$ at 1σ confidence level stats $\Omega_k = +0.21^{+0.08}_{-0.08}$. SNLS SNIa+CMB+SDSS give: $\Omega_m = 0.28^{+0.03}_{-0.02}$, $\Omega_{\mathcal{C}} = 0.037^{+0.003}_{-0.004}$ and $w_r = -2.05^{+0.15}_{-0.15}$ at 1σ confidence level demonstrate $\Omega_k = +0.11^{+0.10}_{-0.07}$. Tables III and IV give the best fit values for free parameters and age of universe computing with these values. Joint confidence intervals in free parameter spaces are shown in figures (8), (9), (10), (11), (12) and (13).

IV. AGE OF UNIVERSE

The age of universe integrated from the big bang up to now in terms of free parameters of thick brane model is given by:

$$t_0(\Omega_m, \Omega_{\mathcal{C}}, w_r, w) = \int_0^{t_0} dt$$
$$= \frac{1}{H_0\sqrt{|\Omega_k|}} \mathcal{F}\left(\sqrt{|\Omega_k|}\int_0^\infty \frac{dz' H_0}{(1+z')H(z')}\right) \quad (41)$$

Figure (14) shows the dependence of $H_0 t_0$ (Hubble parameter times the age of universe) on Ω_m and w_r for a flat universe. Obviously increasing Ω_m and w_r result in a longer and shorter age for the universe, respectively. As a matter of fact, according to the equation (14), $\Omega_m|w_r|$ behaves as dark energy in the ΛCDM scenario and w_r has the same role as w in the ΛCDM (see figures (15)).

TABLE IV. The best values for the curvature of a thick brane model with the corresponding age for the universe from fitting with SNIa from new Gold sample and SNLS data, SNIa+CMB and SNIa+CMB+SDSS experiments at one and two σ confidence level. Here we suppose $w = 0.0$.

Observation	Ω_k	Age (Gyr)
SNIa(new Gold)	$-0.28^{+5.79}_{-1.62}$	$12.54^{+8.85}$
SNIa(new Gold)+CMB	$+0.14^{+0.24}_{-0.22}$	$15.31^{+1.06}_{-1.81}$
SNIa(new Gold)+ CMB+SDSS	$+0.21^{+0.08}_{-0.08}$	$14.72^{+0.43}_{-0.48}$
SNIa (SNLS)	$-0.14^{+1.34}$	$13.50^{+2.95}$
SNIa(SNLS)+CMB	$-0.10^{+0.27}_{-0.74}$	$14.66^{+1.02}_{-4.61}$
SNIa(SNLS)+ CMB+SDSS	$+0.11^{+0.10}_{-0.07}$	$14.18^{+0.26}_{-0.29}$

TABLE V. The value of τ for three high redshift objects, using the parameters of the model derived from fitting with the observations. Here we imagined flat universe and $w = 0.0$.

Observation	LBDS 53W069 $z = 1.43$	LBDS 53W091 $z = 1.55$	APM $08279 + 5255$ $z = 3.91$
SNIa (new Gold)	$0.35^{+0.13}_{-0.02}$	$0.36^{+0.13}_{-0.02}$	$0.16^{+0.07}_{-0.01}$
SNIa(new Gold)+CMB +SDSS	$1.27^{+0.54}_{-0.52}$	$1.36^{+0.58}_{-0.57}$	$0.75^{+0.41}_{-0.37}$
SNIa(new Gold)+CMB +SDSS+LSS	$1.33^{+0.48}_{-0.53}$	$1.41^{+0.52}_{-0.57}$	$0.75^{+0.36}_{-0.38}$
SNIa (SNLS)	$0.85^{+0.64}_{-0.85}$	$0.89^{+0.67}_{-0.89}$	$0.42^{+0.33}_{-0.42}$
SNIa(SNLS)+CMB +SDSS	$1.19^{+0.61}_{-0.64}$	$1.27^{+0.65}_{-0.69}$	$0.67^{+0.41}_{-0.40}$
SNIa(SNLS)+CMB +SDSS+LSS	$1.36^{+0.62}_{-0.62}$	$1.45^{+0.67}_{-0.67}$	$0.78^{+0.45}_{-0.42}$

The "age crisis" is one the main reasons of the acceleration phase of the universe. The problem is that the universe's age in the Cold Dark Matter (CDM) universe is less than the age of old stars in it. Studies on the old stars [76] suggest an age of 13^{+4}_{-2} Gyr for the universe. Richer et. al. [77] and Hasen et. al. [78] also proposed an age of 12.7 ± 0.7 Gyr, using the white dwarf cooling sequence method (for full review of the cosmic age see [13]). To do another consistency test, we compare the age of universe derived from this model with the age of old stars and Old High Redshift Galaxies (OHRG) in various redshifts. Table IV shows that age of the universe from the combined analysis of SNIa+CMB+SDSS is $14.72^{+0.43}_{-0.48}$ Gyr and $14.18^{+0.26}_{-0.29}$ Gyr for new Gold sample and SNLS data, respectively, while ΛCDM implies 13.7 ± 0.2Gyr [13]. These values are in agreement with the age of old stars [76].

Here we consider three OHRG for comparison with the thick brane model, namely the LBDS 53W091, a 3.5-Gyr old radio galaxy at $z = 1.55$ [79], the LBDS 53W069 a 4.0-Gyr old radio galaxy at $z = 1.43$ [80] and a quasar, APM $08279 + 5255$ at $z = 3.91$ with an age of $t = 2.1^{+0.9}_{-0.1}$Gyr [81]. The latter has once again led to the "age crisis". An interesting point about this quasar is that it cannot be accommodated in the ΛCDM model [82]. In order to quantify the age-consistency test we introduce the expression τ as:

TABLE VI. The value of τ for three high redshift objects, using the parameters of the model derived from fitting with the observations. Here we chose $w = 0.0$.

| Observation	LBDS 53W069 $z = 1.43$	LBDS 53W091 $z = 1.55$	APM $08279 + 5255$ $z = 3.91$
SNIa (new Gold)	$0.75^{+0.44}_{-0.75}$	$0.78^{+0.47}_{-0.78}$	$0.35^{+0.27}_{-0.35}$
SNIa(new Gold)+CMB +SDSS	$1.37^{+0.23}_{-0.41}$	$1.46^{+0.25}_{-0.46}$	$0.83^{+0.24}_{-0.45}$
SNIa(new Gold)+CMB +SDSS+LSS	$1.13^{+0.07}_{-0.08}$	$1.19^{+0.07}_{-0.09}$	$0.65^{+0.14}_{-0.07}$
SNIa (SNLS)	$1.10^{+0.34}_{-1.10}$	$1.16^{+0.43}_{-1.16}$	$0.58^{+0.29}_{-0.58}$
SNIa(SNLS)+CMB +SDSS	$1.35^{+0.25}_{-1.31}$	$1.44^{+0.27}_{-1.42}$	$0.80^{+0.22}_{-0.80}$
SNIa(SNLS)+CMB +SDSS+LSS	$1.17^{+0.05}_{-0.05}$	$1.24^{+0.06}_{-0.06}$	$0.67^{+0.14}_{-0.04}$
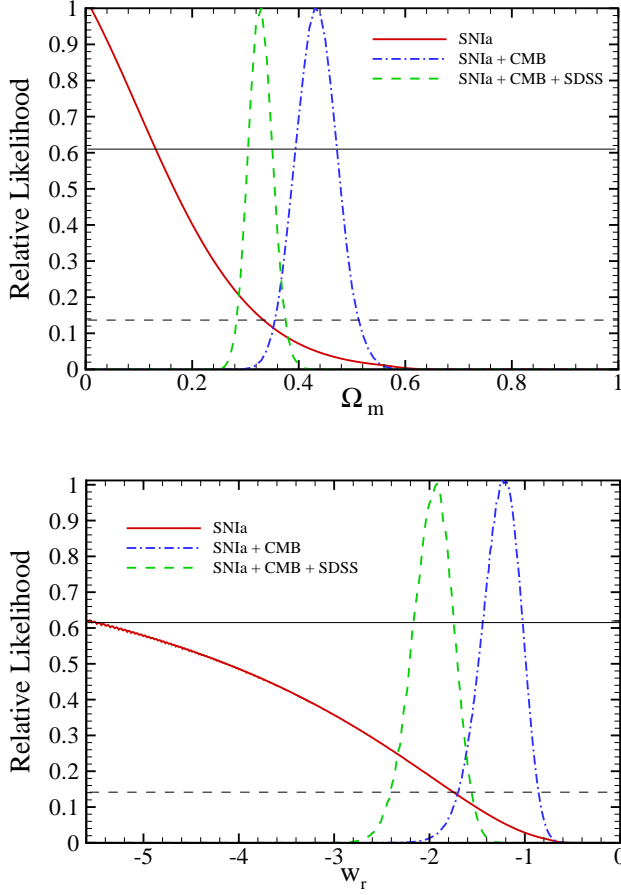
FIG. 4. Marginalized likelihood functions of two parameters of model (Ω_m and w_r). The solid line corresponds to the likelihood function of fitting the model with SNIa data (new Gold sample), the dashdot line with the joint SNIa+CMB data and dashed line corresponds to SNIa+CMB+SDSS. The intersections of the curves with the horizontal solid and dashed lines give the bounds with 1σ and 2σ level of confidence respectively. Here $\Omega_k = 0.0$ and $w = 0.0$.

$$\tau = \frac{t(z; \Omega_m, \Omega_C, w_r, w)}{t_{obs}} = \frac{t(z; \Omega_m, \Omega_C, w_r, w)H_0}{t_{obs}H_0} \quad (42)$$

where $t(z)$ is the age of universe, obtained from the equation (41) and t_{obs} is an estimation for the age of old cosmological object. In order to have a compatible age for the universe we should have $\tau > 1$. Tables V and VI report the value of τ for three mentioned OHRG with various observations. We see that the parameters of thick brane model from the combined observations provide a compatible age for the universe, compared to the age of old objects, also in addition SNLS data result in a shorter age for the universe. Once again for the thick brane model, APM $08279 + 5255$ at $z = 3.91$ has a longer age than the universe but gives better results than most cosmological models investigated before [14,15,82].
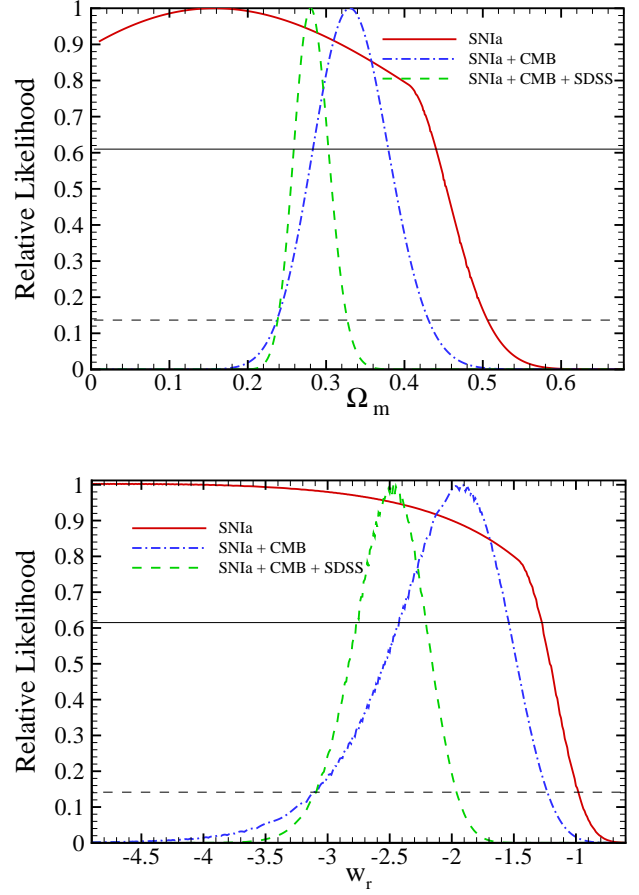
FIG. 5. Marginalized likelihood functions of two parameters of thick brane model (Ω_m and w_r). The solid line corresponds to the likelihood function of fitting the model with SNIa data (SNLS), the dashdot line with the joint SNIa+CMB data and dashed line corresponds to SNIa+CMB+SDSS. The intersections of the curves with the horizontal solid and dashed lines give the bounds with 1σ and 2σ level of confidence respectively. Here $\Omega_k = 0.0$ and $w = 0.0$.

V. CONCLUSIONS AND DISCUSSIONS

From observational point of view, it has been possible to compare theoretical model with the observational results.

We explored the consistency of a thick codimension 1 brane model with the implication of up-to-date luminosity of supernova type Ia observed by two independent groups, new Gold sample and SNLS data set, acoustic peak in the cosmic microwave background anisotropy power spectrum and baryon acoustic oscillation measured by Sloan Digital Sky Survey.

In this scenario, universe is supposed to be dominated by pressureless cold dark matter, which penetrates to the extra dimension, this leads to an acceleration epoch for the universe.
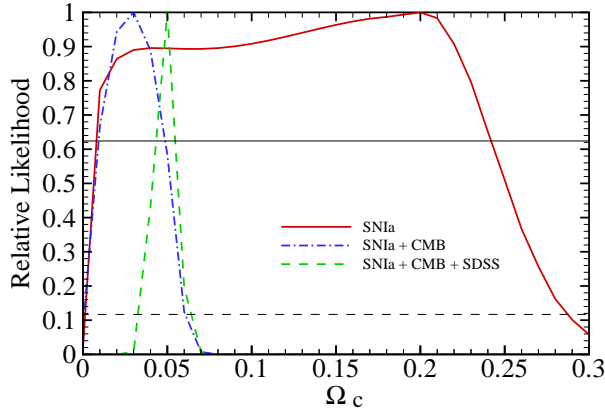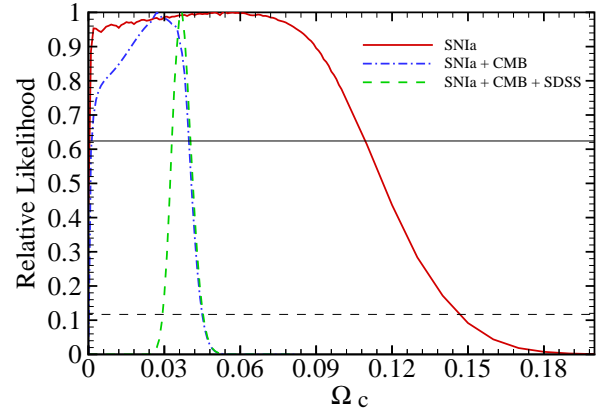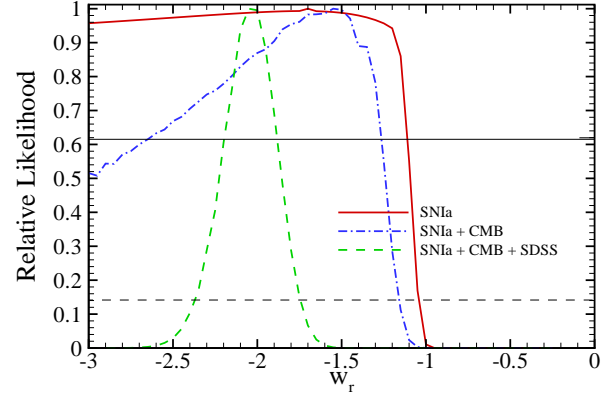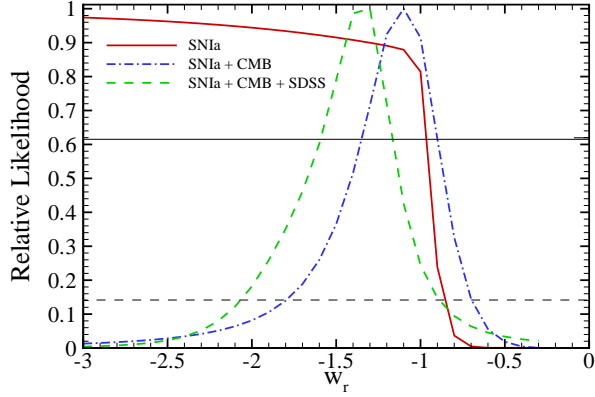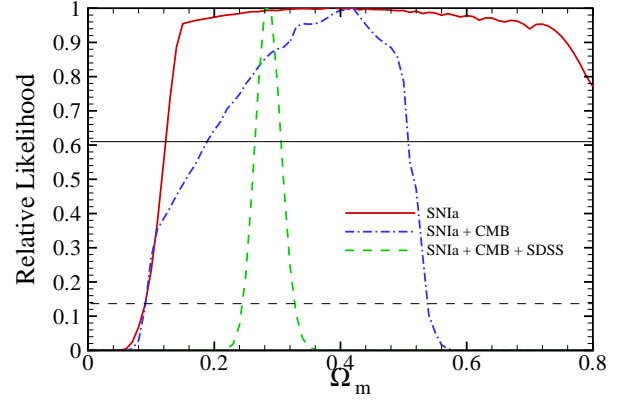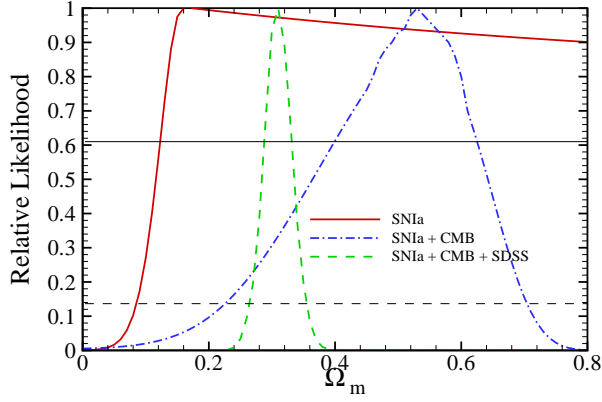
FIG. 6. Marginalized likelihood functions of three parameters of model (Ω_m, w_r and $\Omega_{\mathcal{C}}$). The solid line corresponds to the likelihood function of fitting the model with SNIa data (new Gold sample), the dashdot line with the joint SNIa+CMB data and dashed line corresponds to SNIa+CMB+SDSS. The intersections of the curves with the horizontal solid and dashed lines give the bounds with 1σ and 2σ level of confidence respectively. Here we take $w = 0.0$.

FIG. 7. Marginalized likelihood functions of three parameters of model (Ω_m, w_r and $\Omega_{\mathcal{C}}$). The solid line corresponds to the likelihood function of fitting the model with SNIa data (SNLS), the dashdot line with the joint SNIa+CMB data and dashed line corresponds to SNIa+CMB+SDSS. The intersections of the curves with the horizontal solid and dashed lines give the bounds with 1σ and 2σ level of confidence respectively. Here we take $w = 0.0$.
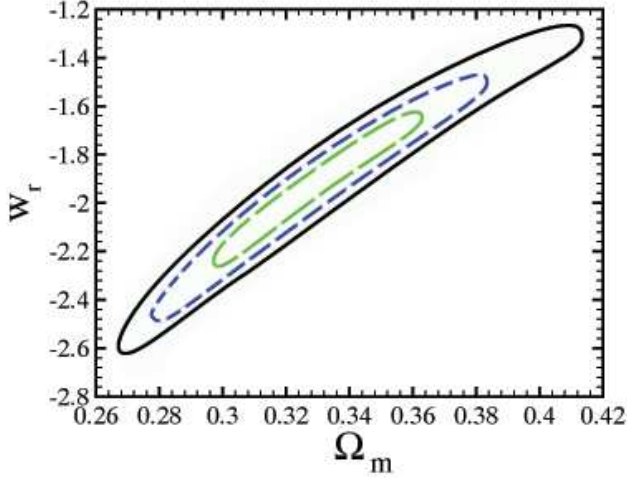
FIG. 8. Joint confidence intervals of Ω_m and w_r, fitted with SNIa new Gold sample+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here $\Omega_k = 0.0$ and $w = 0.0$.

FIG. 9. Joint confidence intervals of Ω_m and w_r, fitted with SNIa SNLS+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here $\Omega_k = 0.0$ and $w = 0.0$.

In this work we have been interested in matter dominated era for the universe. So we imagined $w = 0.0$ as a prior through this paper. The best parameters obtained from the fitting with the new Gold sample data combined with CMB and SDSS observations are: $\Omega_m = 0.31^{+0.02}_{-0.02}$, $\Omega_{\mathcal{C}} = 0.05^{+0.01}_{-0.01}$ and $w_r = -1.40^{+0.20}_{-0.20}$ at 1σ confidence level states spatially open universe with $\Omega_k = +0.21^{+0.08}_{-0.08}$. SNLS SNIa+CMB+SDSS give: $\Omega_m = 0.28^{+0.03}_{-0.02}$, $\Omega_{\mathcal{C}} = 0.037^{+0.003}_{-0.004}$ and $w_r = -2.05^{+0.15}_{-0.15}$ at 1σ confidence level demonstrate $\Omega_k = +0.11^{+0.10}_{-0.07}$. The well-known ΛCDM model implying $-0.06 \le \Omega_k \le +0.02$ [13] and some other interesting models such as Dvali-Gabadadze-Porrati (DGP) which states $\Omega_k = 0.01^{+0.09}_{-0.09}$ and $\Omega_k = 0.01^{+0.04}_{-0.04}$ using Gold sample and SNLS data, respectively [83,84], show a contradiction with our results. In fact having a spatially open universe is ruled out in many models comparing to the observations while in this thick brane model we find out it is not possible to have a spatially flat universe, according to the recent observational tests. The value of w_r given by observational constraints is negative. This shows that instead of dark energy to accelerate the universe, we have a strange effect of matter through the extra dimension with negative pressure.

We also performed the age test, comparing the age of old stars and old high redshift galaxies with the age derived from this model. From the best fit parameters of the model using new Gold sample and SNLS SNIa, respectively, we obtained an age of $14.72^{+0.43}_{-0.48}$ Gyr and $14.18^{+0.26}_{-0.29}$ Gyr, for the universe. These results are in agreement with the age of the old stars. The age of universe in this model is larger than what is given in the other models [13–15,84]

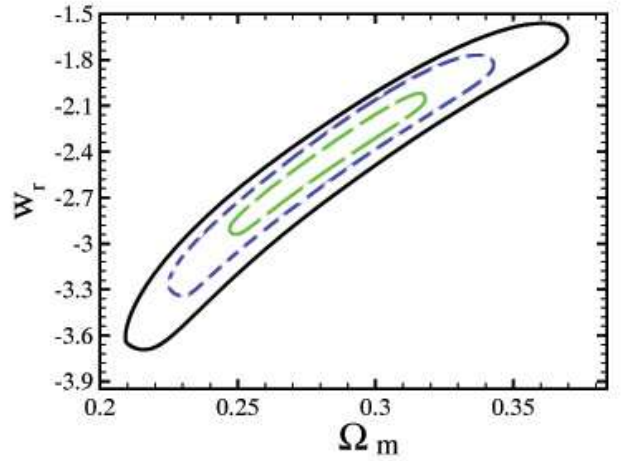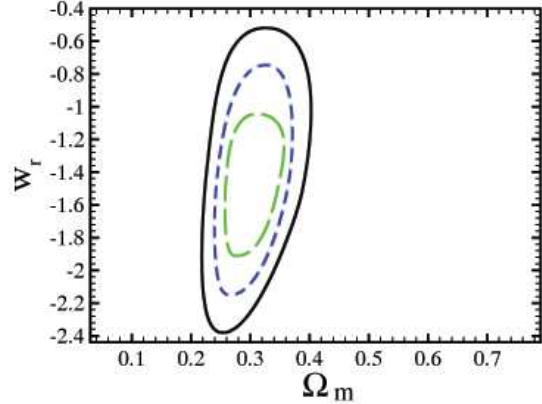To check the age crisis in this model we chose two high

FIG. 10. Joint confidence intervals of Ω_m and w_r, fitted with SNIa new Gold sample+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here we supposed $w = 0.0$.

redshift radio galaxies at $z = 1.55$ and $z = 1.43$ with a quasar at $z = 3.91$. Two first objects were consistent with the age of universe, i.e., they were younger than the universe while the third one was not but gave better result than ΛCDM and a class of Quintessence model [14,15].

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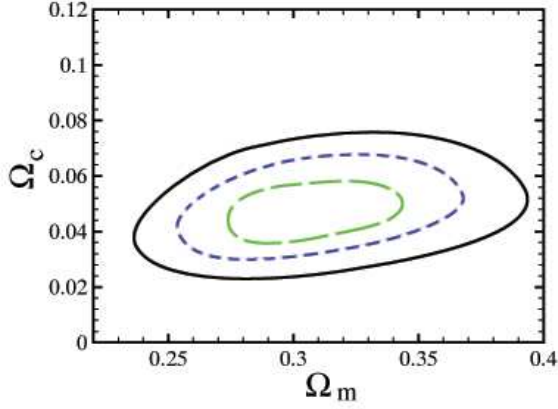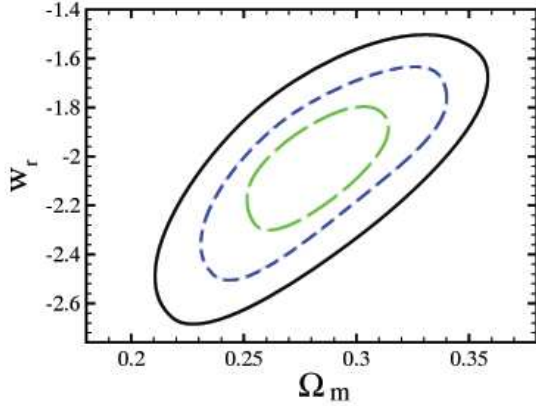[5] Sahni,V. and Starobinsky, A. 2000, Int. J. Mod. Phys. D9, 373

FIG. 11. Joint confidence intervals of Ω_m and $\Omega_{\mathcal{C}}$, fitted with SNIa new Gold sample+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here we fixed $w = 0.0$.

FIG. 13. Joint confidence intervals of $\Omega_{\mathcal{C}}$ and w_r, fitted with SNIa SNLS+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here we fixed $w = 0.0$.
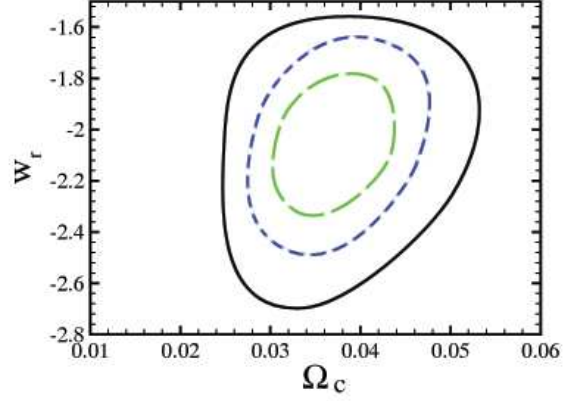

FIG. 12. Joint confidence intervals of Ω_m and w_r, fitted with SNIa SNLS+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively. Here we fixed $w = 0.0$.

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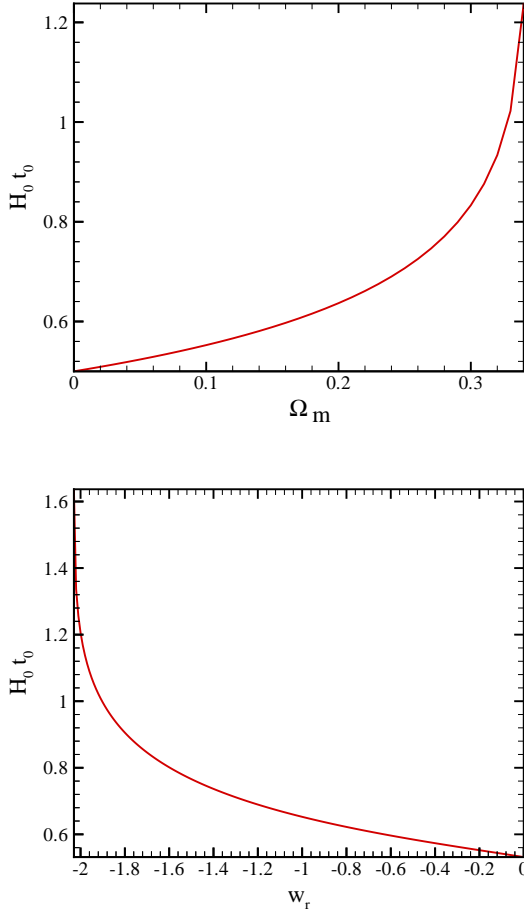
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FIG. 14. $H_0 t_0$ (age of universe times the Hubble constant at the present time) as a function of Ω_m (upper panel) for a flat universe dominated by cold dark matter and typical value of $w_r = -1.92$. Increasing Ω_m gives a longer age for the universe. Lower panel shows the same function versus w_r for the case $w = 0.0$, $\Omega_m = 0.33$ and flat universe.
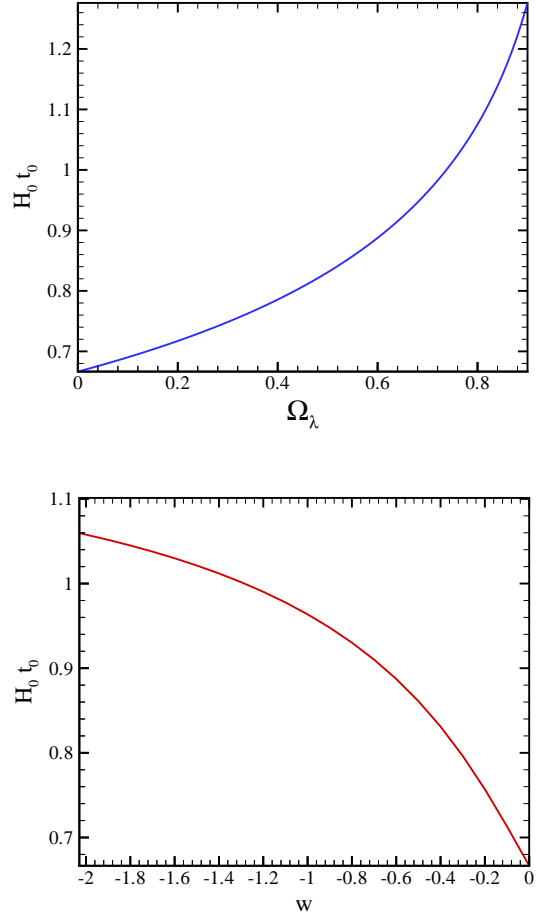
FIG. 15. $H_0 t_0$ (age of universe times the Hubble constant at the present time) versus Ω_λ (upper panel) in the ΛCDM model for the case $\Omega_k = 0.0$ and $w = -1.0$. Lower panel shows $H_0 t_0$ as a function of present equation of state, w, in the ΛCDM model with the typical values $\Omega_m = 0.30$ and $\Omega_\lambda = 0.70$.

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